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NAVORD REPORT 1570

DIFFUSER INVESTIGATIONS IN A SUPERSONIC WIND TUNNEL

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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DIFFUSER INVESTIGATIONS IN A
SUPERSONIC WIND TUNNEL

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ABSTRACT: Some results are presented from the first tests in a program to determine the most efficient diffuser configuration for use in a supersonic wind tunnel. Sufficient data have been obtained at M 2.48 and M 2.83 to make possible the design of a simple yet very efficient diffuser to be used at these Mach numbers in a supersonic wind tunnel with a square cross-section. It has been found that a very efficient tunnel system can be obtained using a simple converging-diverging, variable-throat diffuser if the diffuser throat is located at a point approximately 6.7 times the nozzle exit opening from the nozzle exit. This diffuser should start at a point approximately 1.4 times the nozzle exit opening.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

In this report some data are presented concerning supersonic wind-tunnel diffusers. Utilizing these and subsequent experimental data will make it possible to vastly improve existing installations with regard to running time and greatly reduce the cost of new test facilities with regard to pumping equipment. This work was carried out under ARR-10, Task No. NOL-159 sponsored by the Office of Naval Research during the period from September 1949 to October 1950. Variations of these data in tunnels which are not geometrically similar to the NOL 18 x 18 cm Aerophysics Tunnel No. 3 have not been investigated so far. Further data will be obtained at M 1.86 and M 4.82. The investigations were carried out under the direction of H. H. Kurzweg, Chief of the Aeroballistics Division of the Aeroballistics Research Department at the Naval Ordnance Laboratory.

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Aeroballistic Research Department
By direction

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INTRODUCTION

1. Improving the design of diffusers for superso[illegible] tunnels can contribute greatly toward reducing the cost of [illegible] tunnel research facilities and improving the efficiency of [illegible] of existing installations. The results presented here are ve[illegible] couraging and should be considered in all future wind-tunnel [illegible]

TEST EQUIPMENT

2. Figure 1 shows the NOL 18 x 18 cm Aerophysics Tu[illegible] No. 3 in which these tests were conducted. Figure 2 is a sket[illegible] the same tunnel showing some of the symbols and nomenclature t[illegible] used. The nozzle and diffuser section has a constant width of [illegible] Various sets of nozzles are installed to produce different [illegible] The diffuser in this tunnel is of a special design so that the [illegible] can be placed at almost any point along the entire length of t[illegible] when the surfaces of the diffuser form straight lines. Once the [illegible] has been located at some point the opening can be changed duri[illegible] The diffuser section used for the tests described here was 22[illegible] long with entrance and exit openings 18 cm by 18.2 cm. Connecti[illegible] nozzle to the diffuser are two removable jet plates 25.4 cm lo[illegible] the top and bottom of the tunnel. When these plates are instal[illegible] essentially a closed jet is obtained, while the removal of the[illegible] provides a half-open jet. These jet plates are slightly di[illegible] downstream. The angle of divergence between the two plates is [illegible] than one degree.

THE DIFFUSER PROBLEM

3. If a pitot probe is placed in the test sectio[illegible] undergoes an entropy gain in passing through the normal sh[illegible] of the tube but all of the remaining kinetic energy is tran[illegible] isentropically into pressure, i.e., the air is brought to re[illegible] further losses. This is the same task which must be perfor[illegible] tunnel by the diffuser and the transition duct to the spher[illegible] flow is established, steady supersonic flow is maintained in the test section until the pressure in the sphere rises to some critic[illegible] The more efficiently the diffuser functions, i.e., the higher [illegible]

pressure can rise before breakdown of the flow occurs, the lower will be the power requirements for a continuous tunnel and the longer will be the blowing times in an intermittent tunnel. In undergoing the deceleration from supersonic velocities to rest, the air in the wind tunnel must pass through a shock system. Since the entropy gain through a normal shock increases with the Mach number at which the shock occurs, every effort should be made in the diffuser to produce this normal shock at the lowest obtainable Mach number. This allows higher pressures to occur on the downstream side of the normal shock which in turn mean higher sphere pressures. In order to do this it is necessary to produce in the diffuser oblique shocks which are reflected and terminate in a normal shock at a lower Mach number. It has been found that if the proper combination of oblique shocks and normal shock is produced then the entropy gain through this whole shock system will actually be less than through a single normal shock occurring at the Mach number of the test section as is the case in the pitot probe. To find the best such combination, while using a simple converging-diverging flat-surface diffuser, is the aim of this program. Practically speaking, finding this "proper combination" means finding the best location of the diffuser throat from the nozzle exit in conjunction with the best throat openings.

TEST PROCEDURE

4. To obtain a point on the curves which will be discussed later this procedure was followed:

(a) The blow valve was fully opened.
(b) The diffuser throat was opened sufficiently to establish supersonic flow in the upstream half of the diffuser.
(c) The diffuser was closed to that particular test-point setting.
(d) The pressure in the sphere was allowed to rise slowly until flow broke down in the test section as observed with schlieren apparatus. At the moment breakdown occurred the stagnation pressure in the sphere was measured to an accuracy of $\pm$ 0.3 mm Hg.
(e) The blow valve was closed and the diffuser throat opening was measured to an accuracy of $\pm$ 0.1 mm.

TERMINOLOGY USED

5. In this report the term, "pressure recovery", is used to designate the ratio of the pressure in the sphere at the moment flow breaks down in the test section to the pitot pressure in the test section. In symbols this ratio is expressed as p_E/p_p or p end over p pitot. The pitot pressure is used as the basis for comparisons because the pitot tube is well-known and is also a pressure recovery device as discussed above. Actually the value of the pressure recovery changes continuously during a blow but the values referred to here are always the values at breakdown as seen from p_E. This end value is the highest value which is obtained during a blow. Another ratio which is used is the diffuser throat area ratio. This is the ratio of the diffuser throat area, A_d, to the nozzle exit area, A. The length of the diffuser is given as l_d. p_s/p_o is the ratio of the pressure in the sphere when flow is established in the tunnel to the supply pressure which in this tunnel is atmospheric pressure minus the slight pressure drop which occurs in the drier. The values of Mach number, M, recorded here are the average values at the nozzle exit.

RESULTS

6. During the first tests a phenomenon was found to occur in the wind-tunnel diffuser which is similar to the conditions which exist in a ramjet diffuser. This can best be shown by plotting pressure recovery, p_E/p_p, against the diffuser throat area ratio, A_d/A. These pressure recovery curves for M 2.48 and M 2.83 are shown in figures 3 and 4. They were obtained using a closed jet with no obstructions in the tunnel and with the diffuser throat located at 42 percent l_d from the beginning of the diffuser. A curve similar to this one is obtained for any location of the diffuser throat. This curve shows that an optimum value of pressure recovery is obtained at some diffuser throat opening. However, the tunnel cannot be started with this arrangement. The diffuser throat must be opened to some larger value, resulting in a lower pressure recovery, in order to establish supersonic flow in the tunnel. The large increase in pressure recovery which can be obtained by closing the diffuser throat, once flow has been established, results in a tremendous increase in blowing time. With sphere pumps inoperative during the blow, the increase in blowing time for this particular NOL tunnel was calculated to be 50 percent at M 2.48 and 93 percent at M 2.83. These figures show the definite need for a variable-area diffuser in the supersonic wind tunnel. The pressure recovery curve was obtained for six different locations of the diffuser throat at M 2.48 and M 2.83. From each curve an optimum value of pressure recovery was obtained. Figures 5 and 6 show these optimum values plotted against the location of the diffuser throat

in percent l_d. These curves show that the best location of the diffuser throat is 42 percent l_d from the beginning of the diffuser. This 42 percent corresponds to a position 6.7 times the tunnel width from the nozzle exit. These curves show how important it is to an efficient tunnel system to know prior to the design of a tunnel where the diffuser throat must be located. Figures 7 and 8 show the pressure recovery curves obtained using a half-open jet and clear tunnel with the diffuser throat at 42 percent l_d. Comparing these curves with the closed-jet curves shows that using the half-open jet the pressure recovery is not essentially changed. It is frequently more convenient to operate the tunnel with a half-open jet. Other blows were made to determine the effect of a model on the values of pressure recovery. Figures 9 and 10 show the results using a 60° cone with a 3 cm base mounted on a sting in a segment. It can be seen that the model effect is indeed significant. It should be pointed out that this is as large a model as it is advisable to use in a tunnel of this size. Figures 11 and 12 give the results of data obtained from tests made to determine how far down the sphere pressure had to be taken in order to establish flow in the tunnel and at the same time the smallest diffuser throat openings at which flow could be started. The starting pressures are given as the ratio of the sphere pressure to supply pressure. It can be seen that power requirements need only be such as would be necessary to produce sphere pressures at the top of the straight line portion of the curves. The minimum diffuser throat area for starting is given by the nozzle throat area times the reciprocal of the pitot ratio when one assumes no boundary layer. Analysis of the curves of figures 11 and 12 indicates that approximately 4 percent should be added at M 2.48 and 6 percent at M 2.83 to the theoretical area to take care of the boundary layer which exists in the diffuser.

COMPARISON OF RESULTS WITH OTHER DATA

7. Figure 13 shows a comparison of NOL diffuser efficiencies with the best stable values obtained by Neumann and Lustwerk in reference (a) for a constant-shape diffuser. Also listed are the computed maximum efficiencies for the constant-shape diffuser using a one-dimensional analysis. Since the MIT test data are not available the NOL values of efficiency, η, shown have been computed in the MIT manner; namely,

$$\eta = \frac{\frac{2}{\gamma-1}\left[\left(\frac{P_3}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{M_1^2 - \frac{V_2^2}{g\gamma R T_1}}$$

These data are presented to give an indication of the savings in power which are possible using a variable-area rather than a constant-shape diffuser. Neumann and Lustwerk calculated that "if the diffuser efficiency of a tunnel operating at a Mach number of 2.0 is increased from 60 to 85 percent, the power required to drive the tunnel is reduced by 30 percent". This closely approximates the experimental values obtained at NOL. The 18 x 18 cm Aerophysics Tunnel No. 3 was designed to operate continuously on the three pumps available. With the improved diffuser this continuous operation can very easily be obtained using only two pumps. Another comparison is made in Figure 13 between NOL data and the work described in reference (b) where efficiency is given by $\eta = 1 - \frac{2}{\gamma - 1} \frac{1}{M_1^2} \left[\left(\frac{P_o}{P_o'} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$. It can be seen from the values listed that the NOL values slightly exceed the theoretical optimum values which were obtained with simplifying assumptions. A third comparison can be made in Figure 13 with the values of pressure recovery given for one of the original German tunnels from Kochel which is now installed at NOL. The nozzle exit is 40 x 40 cm and is followed by a full-open jet. 34.3 cm straight jet plates are hinged at a point 61.6 cm from the nozzle exit. The diffuser section is 50 cm wide. The diffuser consists of a curved sheet 255 cm long which is deformed during flow by 3 screw jacks. Since the values of pressure recovery obtained in the 18 x 18 cm, closed-jet, square tunnel using a straight-line diffuser are nearly double the values obtained in the 40 x 40 cm tunnel the design of future wind tunnels is strongly indicated. This fact was discussed in reference (c).

APPLICATION OF DATA

8. The information now available makes it possible to design a simple yet efficient diffuser for a supersonic wind tunnel geometrically similar to the NOL 18 x 18 cm Aerophysics Tunnel #3 and operating within the Mach number range tested. Figure 14 shows a proposed design for such a diffuser. It could be made of wood, rubber, and a few commercially available metal pieces for a very small fraction of the cost of present, less efficient diffusers.

FUTURE PLANS

9. The data already obtained will be supplemented with similar tests at M 1.86 and M 4.82. The effect of producing two or more oblique shocks upstream of the diffuser throat by proper wall configurations will also be investigated.

REFERENCES

(a) Neumann, E. P. and Lustwerk, F. "Supersonic Diffusers for Wind Tunnels", Journal of Applied Mechanics, June, 195-202 (1949).

(b) Ferri, Antonio. Elements of Aerodynamics of Supersonic Flows. New York: Macmillan (1949).

(c) Kurzweg, H. H. "A Few Aspects of Future Supersonic Wind-Tunnel Design and Test Techniques", Symposium on Experimental Compressible Flow, NOLR 1133, 103-119 (1949).

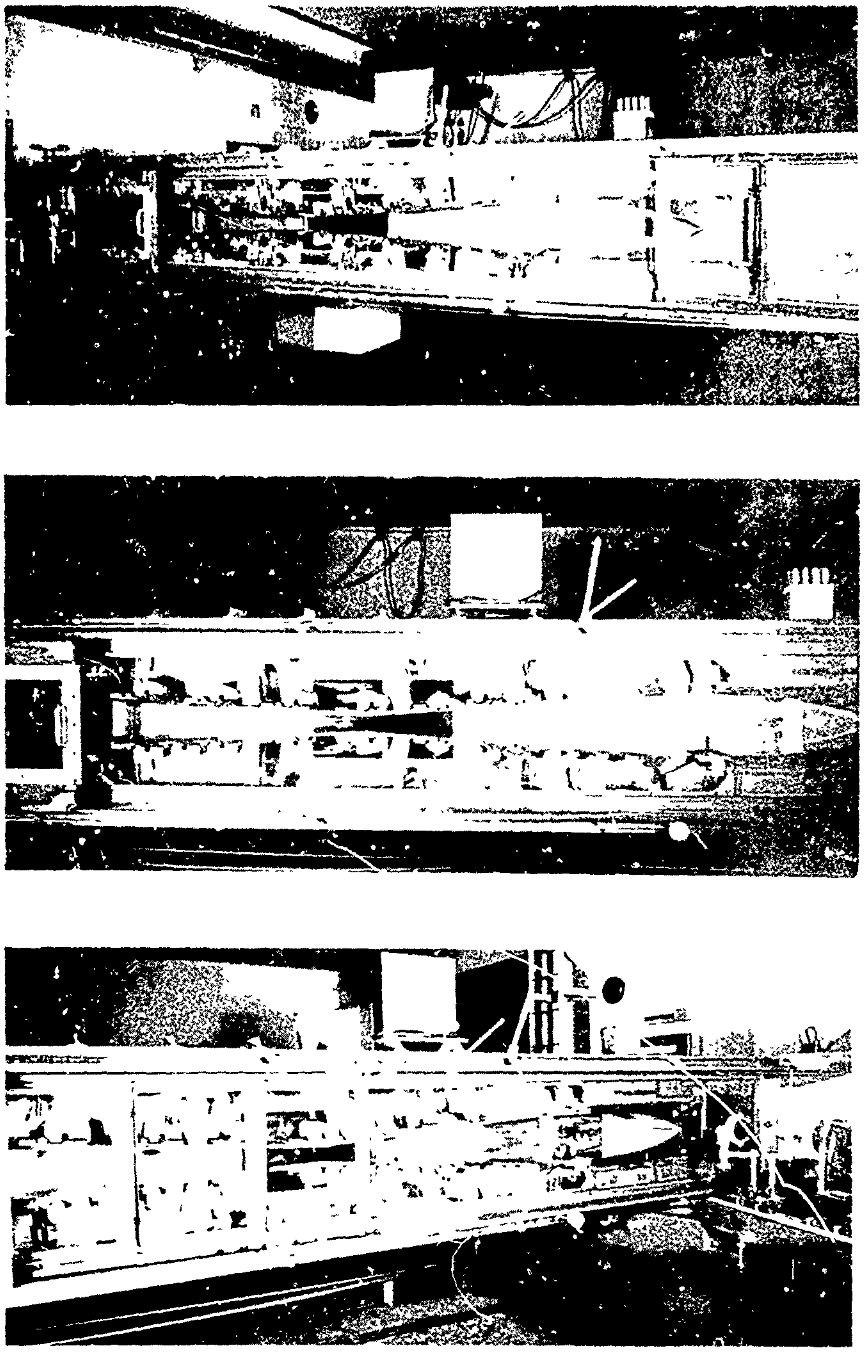

FIG.1 NOL 18X18 CM AEROPHYSICS TUNNEL NO.3

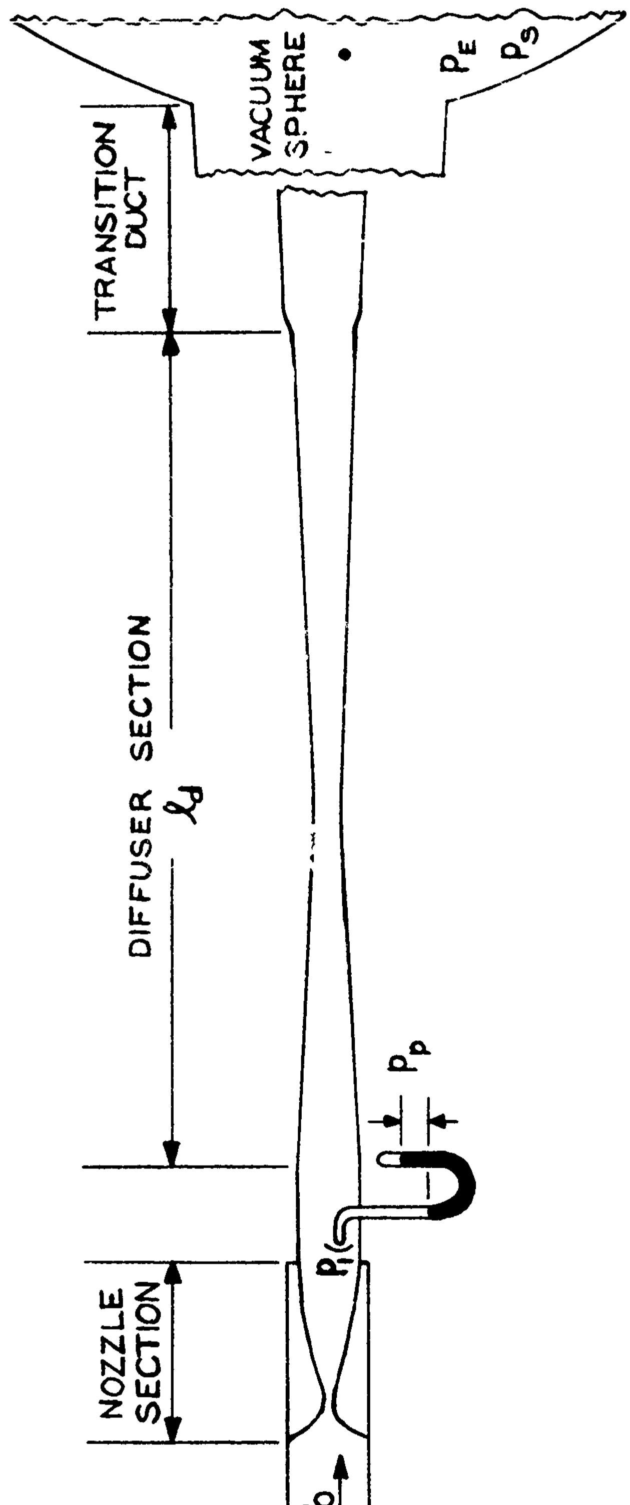

Fig. 2 - SKETCH OF NOL 18 X 18 CM AEROPHYSICS TUNNEL NO 3

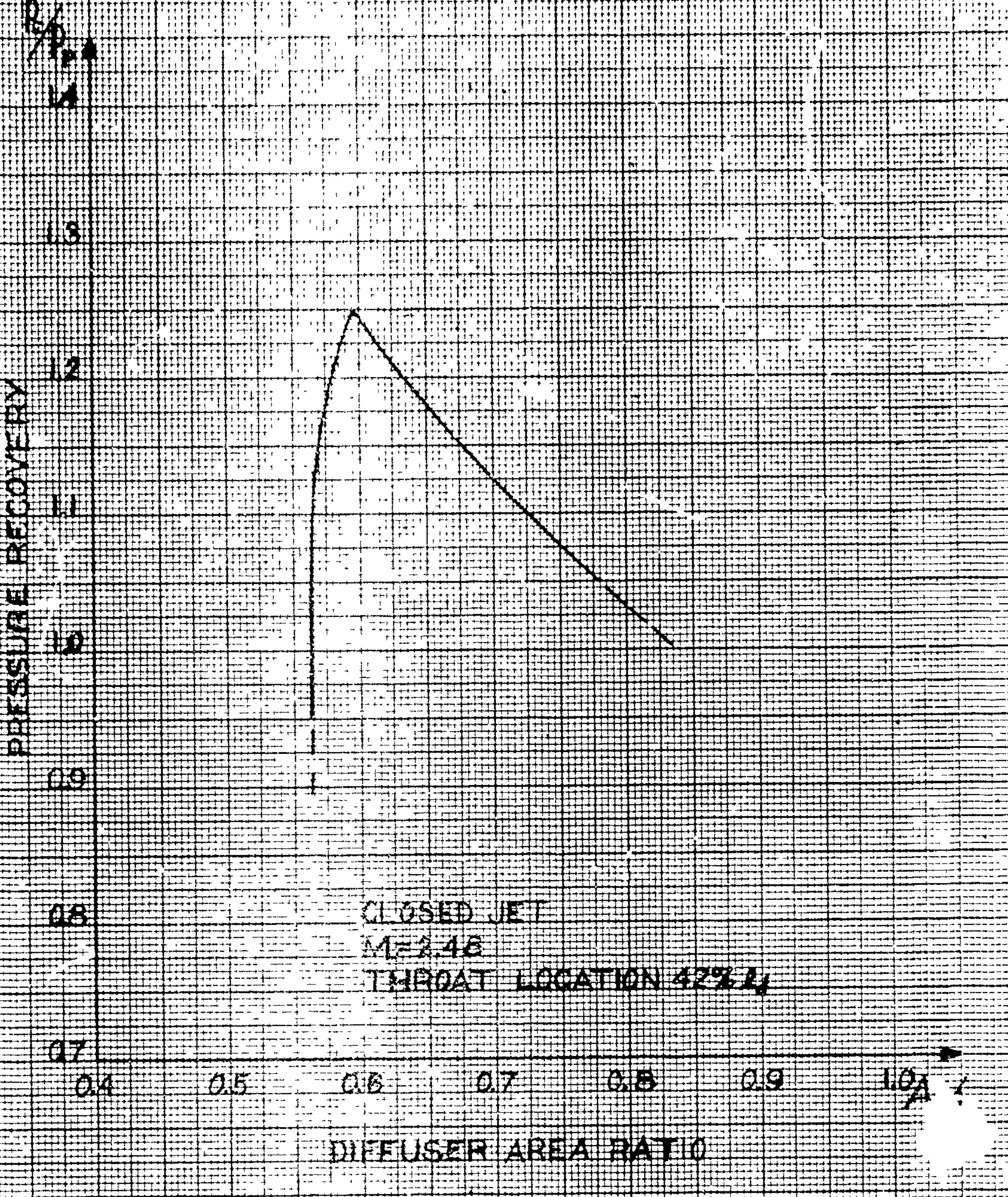

Fig.3-PRESSURE RECOVERY VS DIFFUSER AREA RATIO

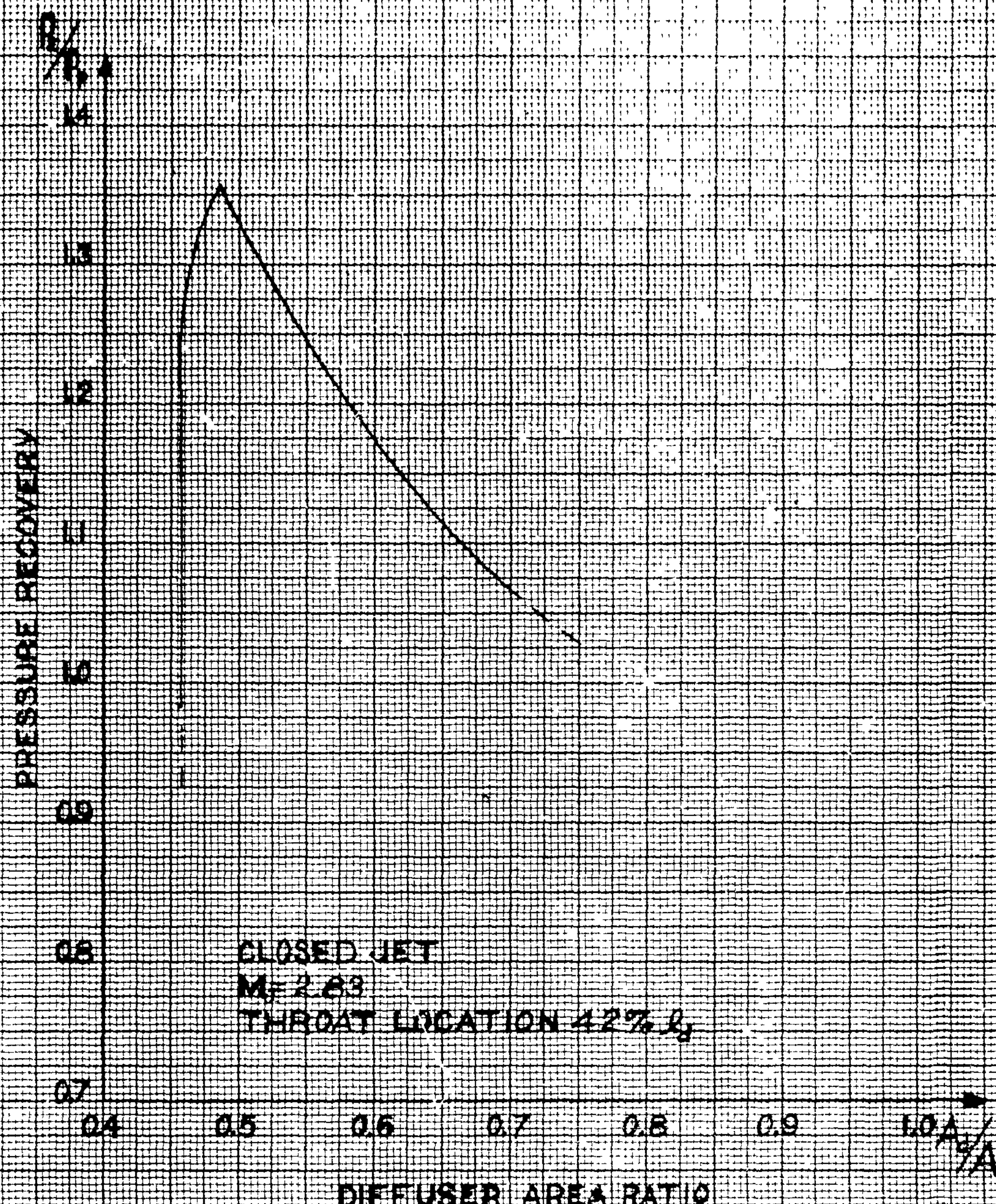

Fig.4 - PRESSURE RECOVERY VS DIFFUSER AREA RATIO

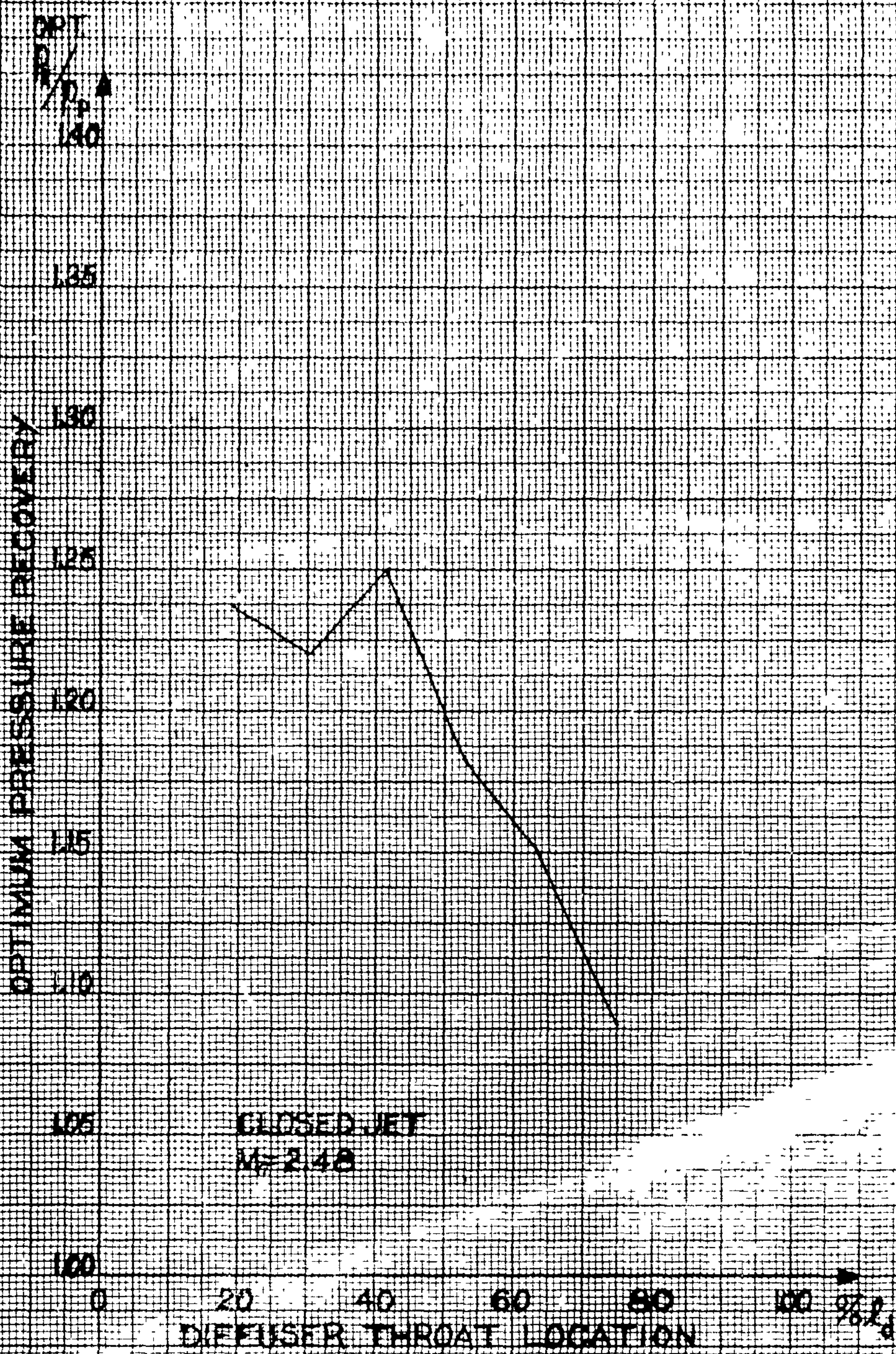

Fig. 5 - OPTIMUM PRESSURE RECOVERY V/S DIFFUSER THROAT LOCATION

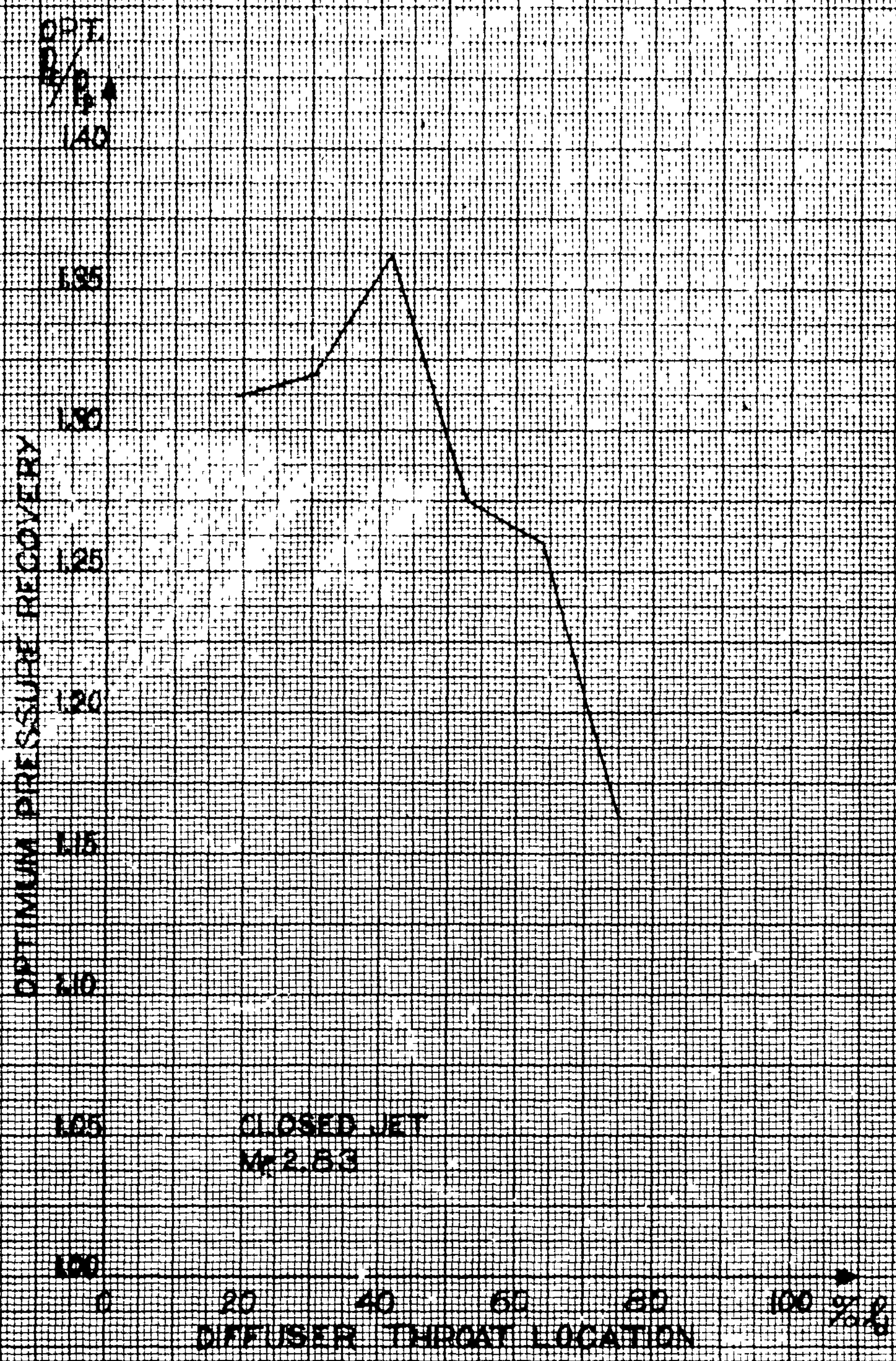

Fig. 6—OPTIMUM PRESSURE RECOVERY VS DIFFUSER THROAT LOCATION

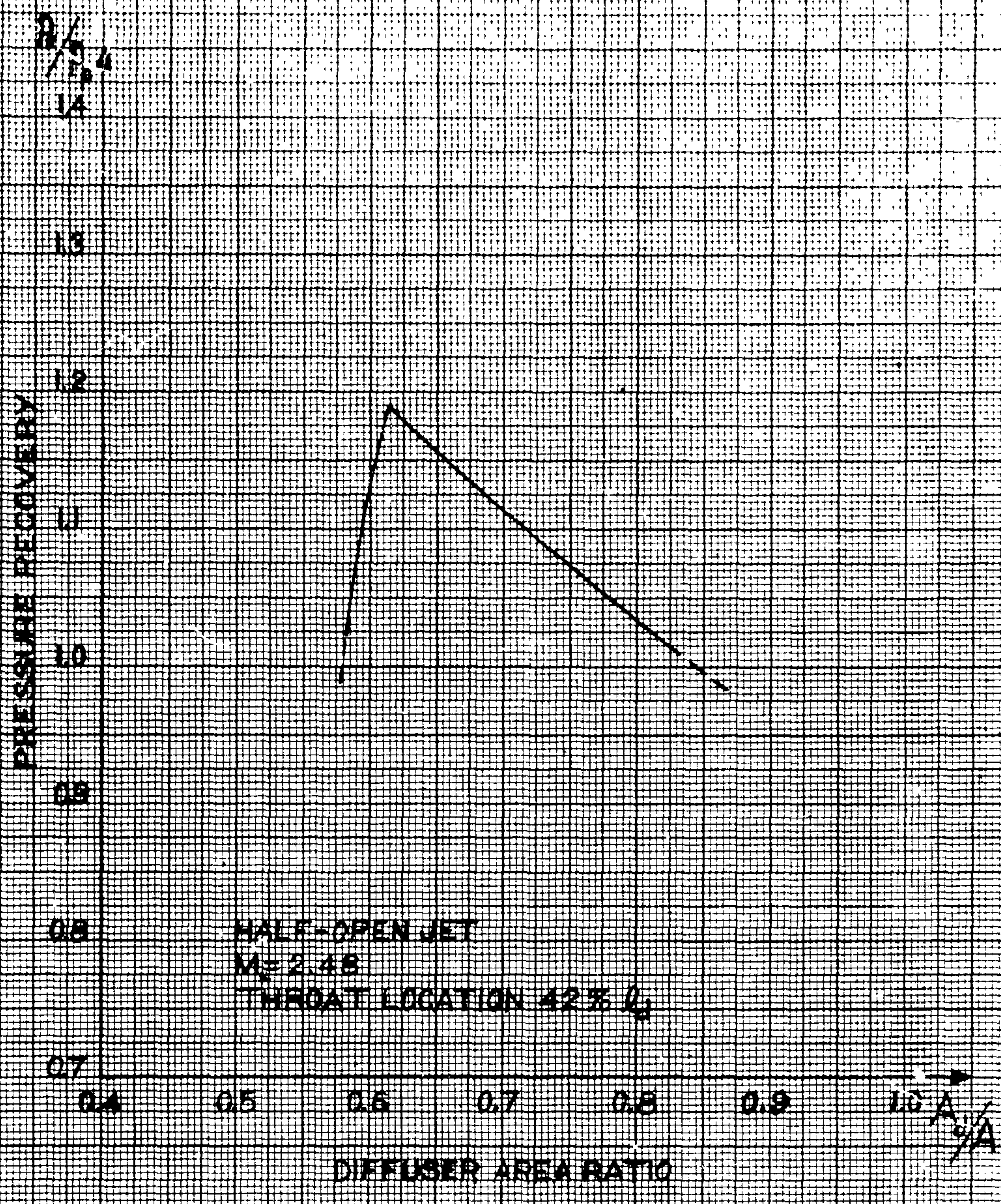

Fig. 7 - PRESSURE RECOVERY VS DIFFUSER AREA RATIO

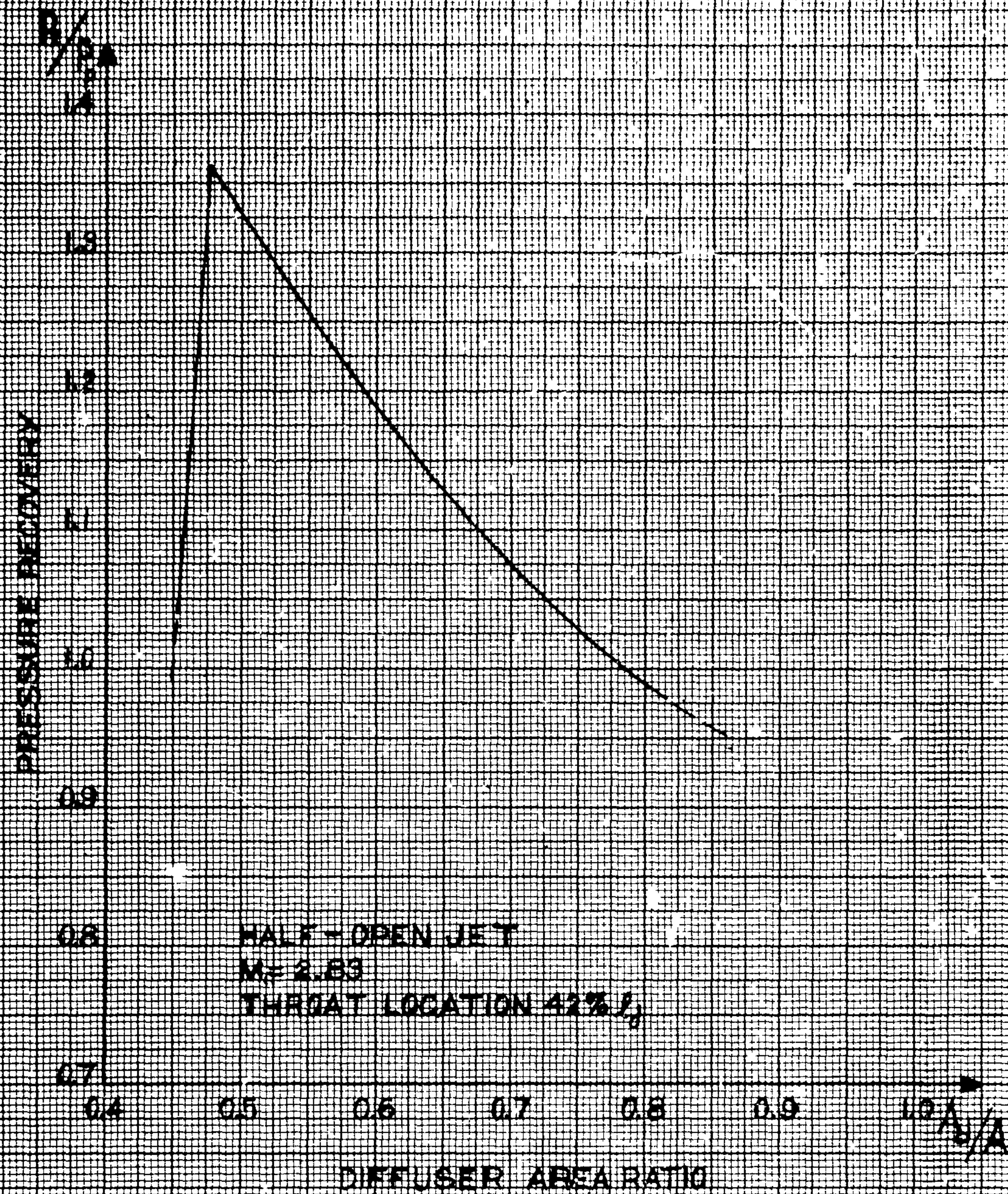

Fig. 8 - PRESSURE RECOVERY VS DIFFUSER AREA RATIO

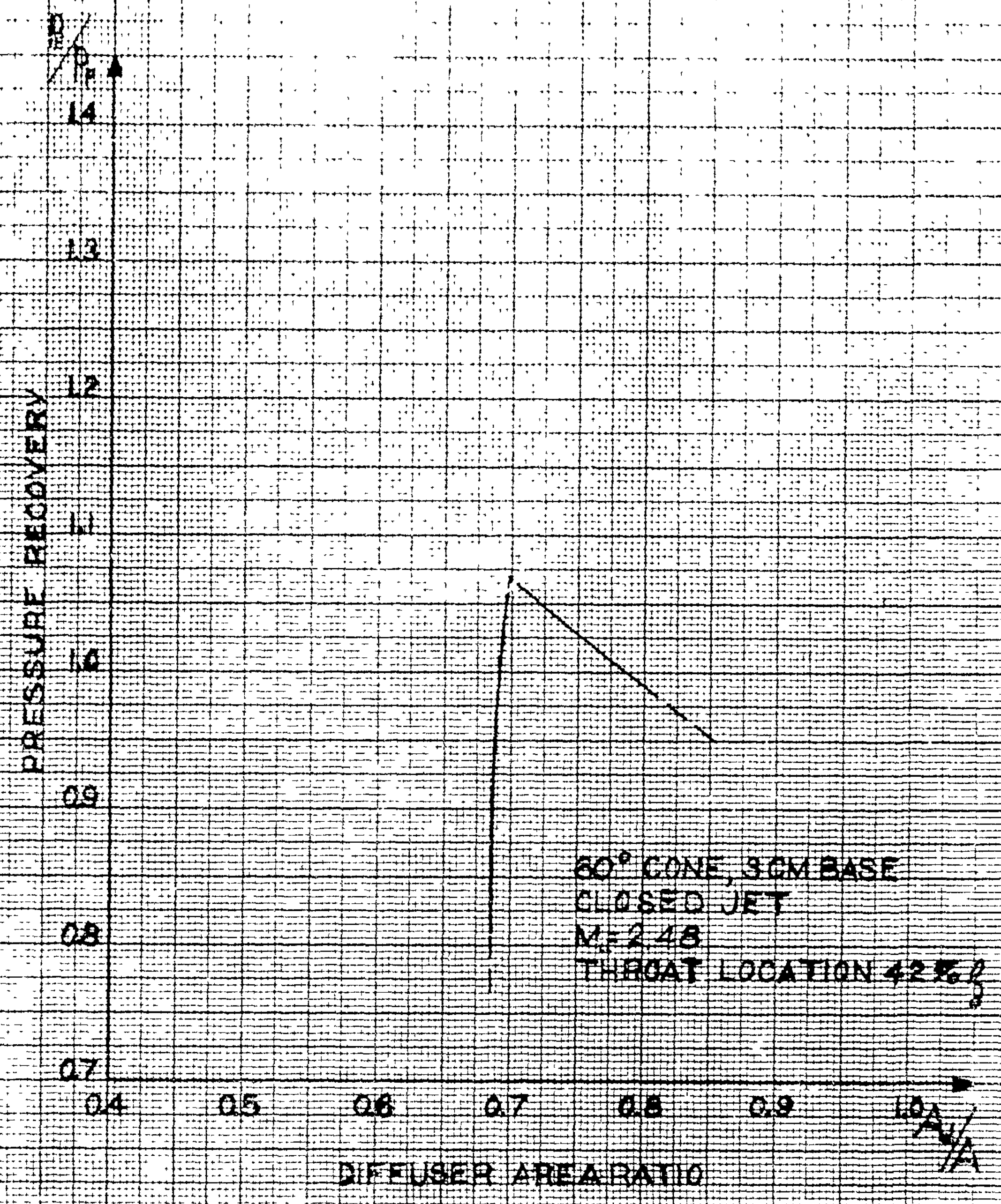

FIG. 9 - THE EFFECT OF A MODEL ON PRESSURE RECOVERY

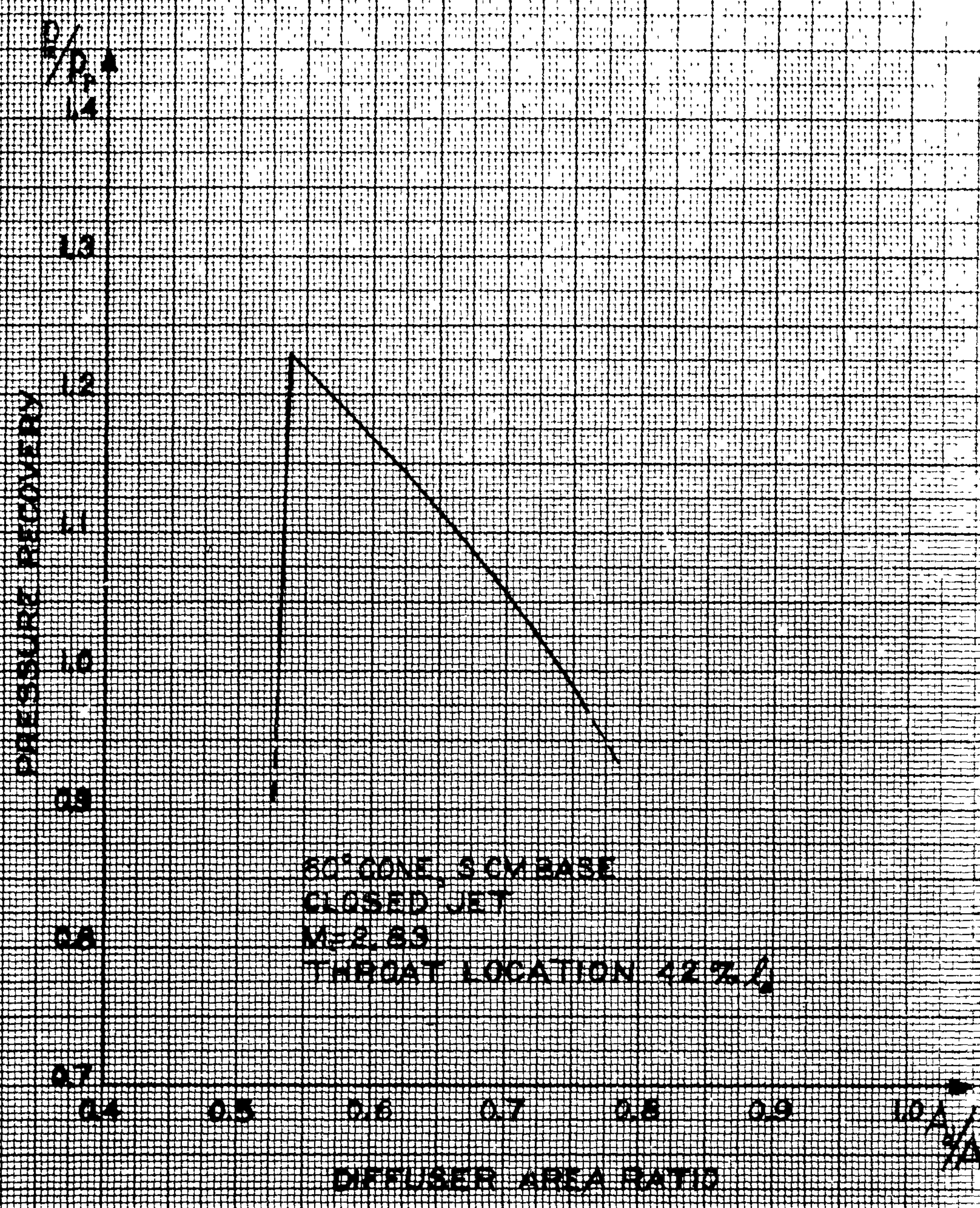

Fig.10 – THE EFFECT OF A MODEL ON PRESSURE RECOVERY

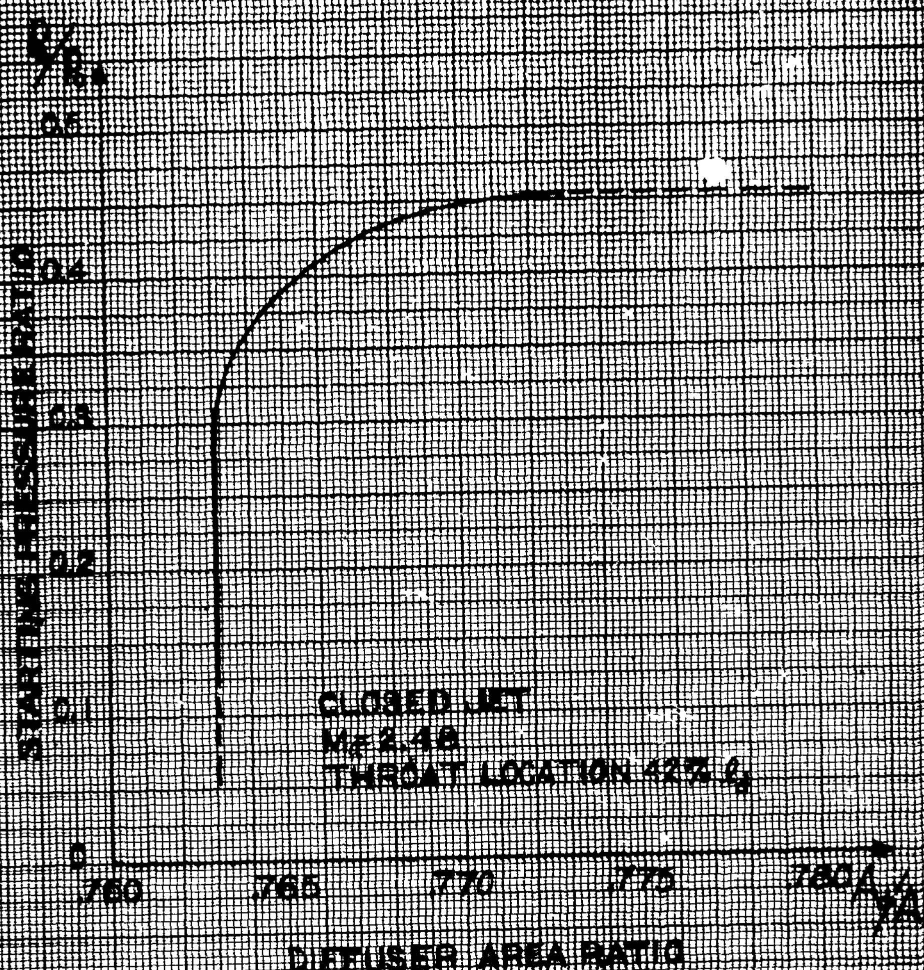

Fig. 11 - STARTING PRESSURE RATIO VS DIFFUSER AREA RATIO

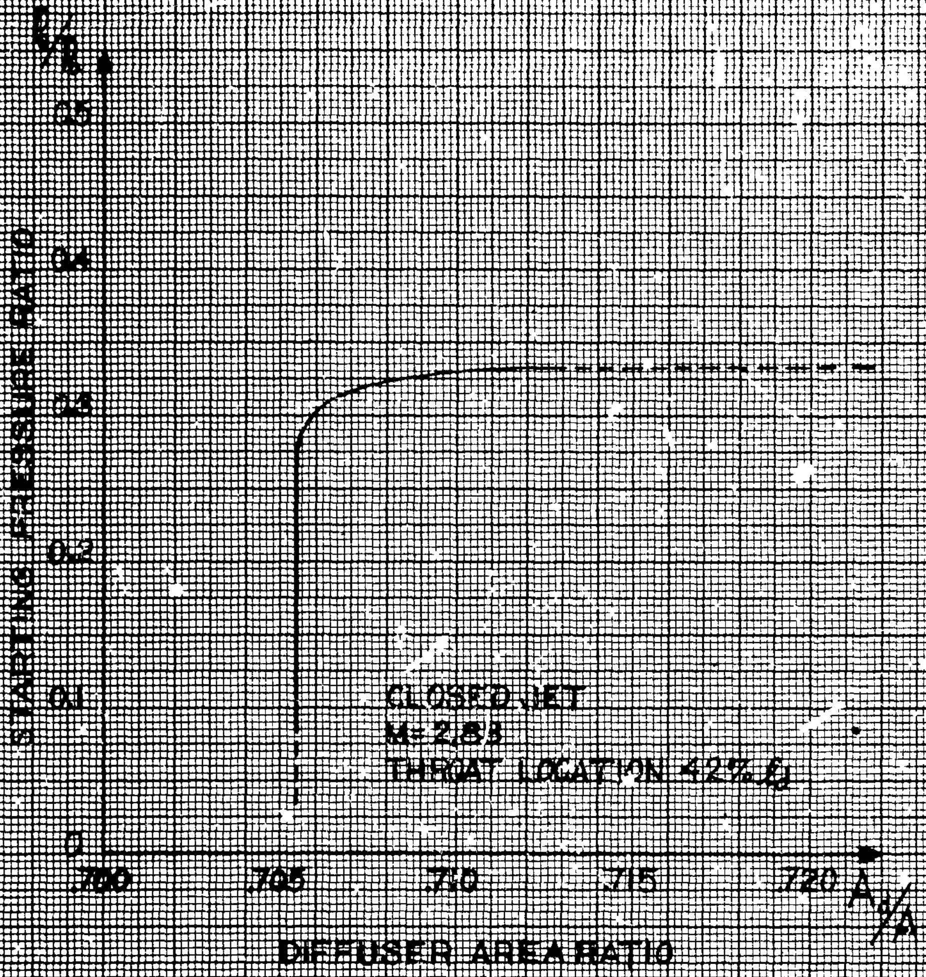

Fig.12 - STARTING PRESSURE RATIO VS DIFFUSER AREA RATIO

	η (M 2.48)	η (M 2.83)
NOL (Experimental values with variable-area diffuser)	.777	.720
MIT (Best stable, experimental values with constant-geometry diffuser)	.71	.64
MIT (Computed maximum for constant-geometry diffuser--using one-dimensional analysis)	.78	.706

	η (M 2.48)	η (M 2.83)
NOL (Experimental values with variable-area diffuser)	.886	.870
Ferri in reference (b) (Theoretical optimum obtained by simplifying assumptions)	.88	.865
Ferri in reference (b) (Divergent diffuser without the convergent part - assuming that the compression occurs with a normal shock at the M in front of the diffuser)	.825	.80

	p_E/p_p (M 2.48)	p_E/p_p (M 2.83)
NOL (18 x 18 cm Aerophysics Tunnel No. 3)	1.25	1.36
NOL (40 x 40 cm Aeroballistics Tunnel No. 1)	.725	.717

Fig. 13 - COMPARISON OF DIFFUSER EFFICIENCIES

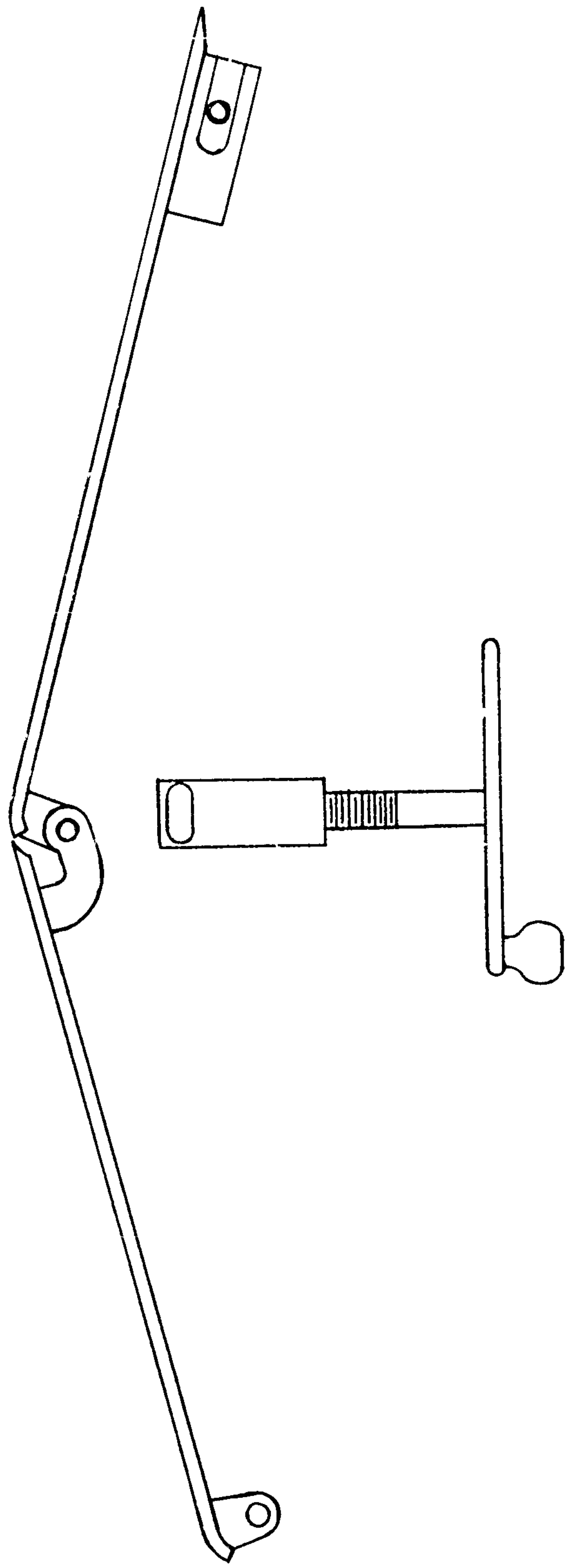

Fig. 14 — PROPOSED DIFFUSER FOR SUPERSONIC WIND TUNNELS